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Design premises for canister for spent nuclear fuel

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1 INTRODUCTION

The purpose of this report is to establish the basic premises for designing canisters for the deposal of spent nuclear fuel, the requirements for canister characteristics, and the design criteria, and to present alternative canister designs that satisfy these premises. The point of departure for canister design has been that the canister must be able to be used for both BWR and PWR fuel.

2 BASIC PREMISES

The spent fuel that is generated by the Swedish nuclear power programme must be able to be encapsulated for emplacement in a final repository in such a manner that safety is maintained at a high level during:

- encapsulation
- transport
- emplacement
- final disposal

The controlling condition is safety in final disposal. At final disposal, all threats to the integrity of the canister and risks of leakage to the biosphere must be dealt with by a suitable choice of design and materials. In other stages of canister handling, the integrity of the canister can be guaranteed by protective measures, such as the use of cushioning material around the canister, and shock-absorbing and radiation-shielding devices.

3 REQUIREMENTS ON FUNCTION AND PROPERTIES

3.1 FUEL TYPES

The essential properties of BWR and PWR fuel are enumerated in Table 1.

Table 1. Fuel properties of importance for canister design.

FUEL TYPE	BWR	PWR
Overall length	4.398 m	4.243 m
Cross-sectional area	140x140 mm^2	214x214 mm^2
Number of fuel rods	63-100	15x15 or 17x17
Enrichment (% U-235)	max. 3.6% (with Gd 4.2%)	max. 4.2%
Burn-up (max.)	55 MWd/kg U	60 MWd/kg U
Burn-up (average)	38 MWd/kg U	42 MWd/kg U
Decay (min.)	30 years	30 years
Decay heat per assembly	100-150 W	300 - 450 W

The spent BWR fuel will be encapsulated together with fuel channels and the spent PWR fuel with control rods. The dimensions in Table 1 are the design-basis dimensions. There are several different fuel types in use with slightly different dimensions. There are also special fuel types, such as MOX fuel and Ågesta fuel, which may require special canister insert sizing. It shall also be possible to encapsulate fuel elements with leaking fuel rods.

3.2 SAFETY: GEOLOGIC REPOSITORY

It is estimated that the Swedish nuclear power programme will give rise to 7800 tonnes of spent nuclear fuel by 2010. This fuel will be disposed of in granitic rock at a depth of about 500 m. Leakage of radioactive substances from this repository will be prevented by a multibarrier system consisting of the fuel itself, a corrosion-resistant canister, a bentonite buffer, and the overlying rock mass. The canister will prevent all dispersal of radioactivity to the surrounding rock, as long as it is intact. The other barriers can retard and attenuate radionuclide dispersal to acceptable levels if the canister starts to leak.

Intended function:

The function of the canister in the geologic repository is to isolate the spent fuel from the surrounding environment. This requirement is interpreted to mean that the canister should completely isolate the waste and that no known corrosion processes should be able to violate the integrity of the canister for at least 100,000 years. This requirement on canister integrity leads to requirements on:

- initial integrity.
- chemical resistance in the environment expected in the repository.
- mechanical strength under the conditions expected to prevail in the repository.

To meet the requirement that other barriers should retard and attenuate radionuclide dispersal to acceptable levels if the canister begins to leak, the requirement must also be made that the canisters must not have any harmful effect on other barriers in the repository. This imposes requirements on:

- choice of a canister material that does not adversely affect buffer and rock.
- limitation of heat and radiation dose to the near field.
- a configuration such that the fuel in the canister remains subcritical even if water enters the canister.
- limitation of the canister's downward pressure against the bentonite.

3.2 SAFETY: OPERATION

Stringent requirements are placed on safety in operation and maintenance of the encapsulation plant. The canister design must satisfy the requirements arising from normal and exceptional operating cases in the encapsulation plant. This means that the canister must be able to be:

- fabricated in serial production with a capacity of 200 canisters per year in compliance with specified quality requirements.
- handled so that no foreseeable accidents lead to exposure of personnel and plant to unacceptable radiation doses or releases of radioactive material.
- transported to the repository and emplaced in a safe manner.
- retrieved, if necessary, from the repository in a safe manner.

4 DESIGN CRITERIA

4.1 SAFETY: GEOLOGIC REPOSITORY

4.1.1 Integrity

Long-term integrity is considered in three categories: initial integrity, corrosion resistance and strength.

Initial integrity

The canisters must be intact when they leave the encapsulation plant.

The canisters must be fabricated, sealed and inspected with methods that guarantee that no more than 0.1% of the finished canisters will contain defects that are larger than the acceptance specifications for non-destructive testing.

Chemical resistance

No known corrosion processes will lead to a canister life of less than 100,000 years in the deep repository.

The hazard index of the fuel as a function of time is illustrated in Figure 4-1. The curve applies for ingestion with food, but the curve is roughly the same for inhalation as well. A hazard index of 1 corresponds to the toxicity of the 8 tonnes of natural uranium with daughters, the amount from which 1 tonne of fuel would have been fabricated. As is evident from the figure, the hazard index for the more readily accessible radionuclides declines to low levels due to decay during the first three hundred years. The largest contribution to the hazard index of the fuel comes from the actinides. Curium and americium dominate during the first thousand years, after which the isotopes of plutonium make the largest contribution up to about 100,000 years, when the decrease in activity of ^{239}Pu starts to become noticeable.

The decay heat in the fuel is generated primarily by fission products during the first few hundred years. From a radiotoxicological viewpoint, isolation of the fuel for 1,000 years corresponds to a reduction by approximately a factor of 10, but also entails that most of the more readily accessible radionuclides have decayed. It takes another 50,000 years for a further ten-fold reduction to be obtained.

Isolation for 100,000 years would reduce the toxicity of the fuel by a factor of more than 100, plutonium would be reduced ten-fold and the toxicity of the fuel would be comparable to that of the uranium from which it had been fabricated.

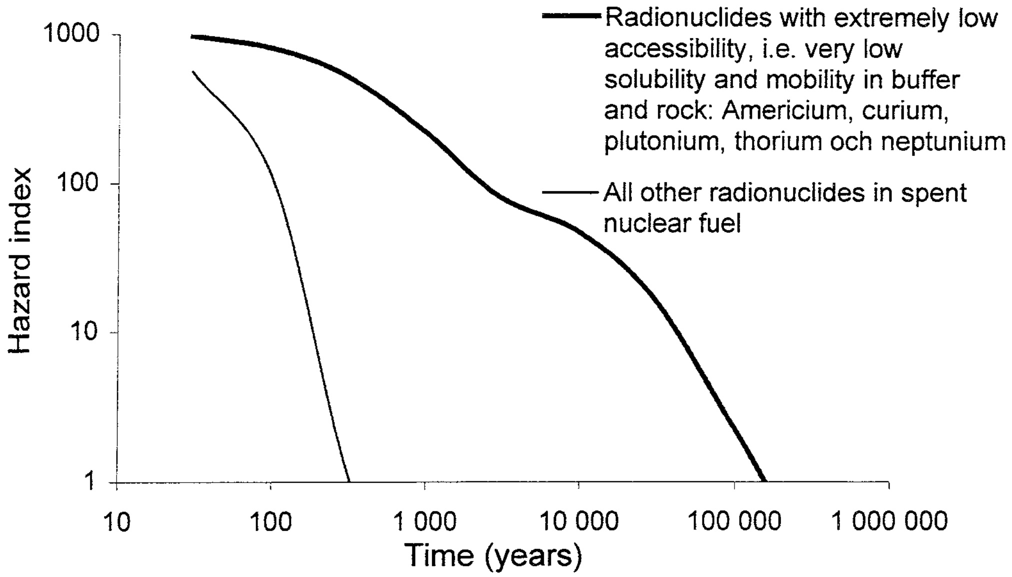


Figure 1: Hazard index of spent nuclear fuel as a function of time

Mechanical strength

The canister must withstand a load equivalent to 14 MPa of external pressure with the usual safety margins.

The design-basis swelling pressure has been set at 7 MPa /Bäckblom/. The design-basis hydrostatic pressure has been set to 7 MPa.

Case 1 Normal load

The canisters must withstand deposition at a depth of 700 m in granitic rock, surrounded by bentonite clay. This entails an evenly distributed load of 7 MPa of hydrostatic pressure and 7 MPa of swelling pressure from the bentonite. These pressures are regarded as additive and isostatic. The canister should be designed for these loads with the customary safety margins.

Case 2 Ice load

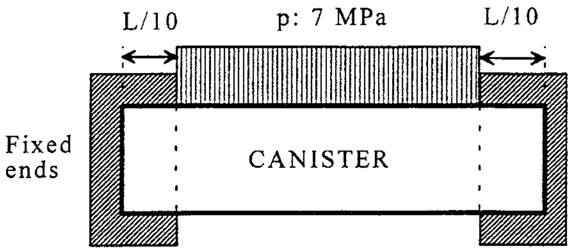
The strength of the canister must also be calculated for a postulated increase in hydrostatic pressure due to glaciation. In this case, 30 MPa is added to the groundwater pressure of 7 MPa, corresponding to an ice cap approximately 3,000 m thick. The total groundwater pressure is then 37 MPa, and with the bentonite's swelling pressure the total pressure is 44 MPa. This load case is to be regarded as an extreme case for which no extra safety margins are required.

Uneven pressure build-up in the bentonite

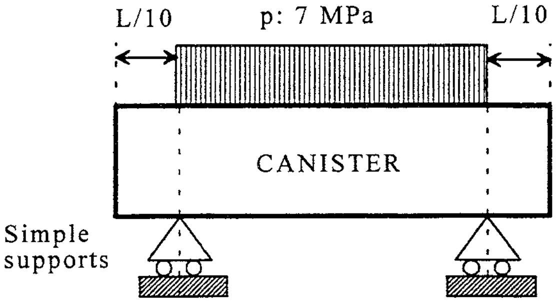
Uneven pressure build-up can occur both during and after the water saturation phase. The design criteria for the mechanical strength of the canister are discussed in detail in Appendix 1. A brief summary is given below.

Water saturation phase

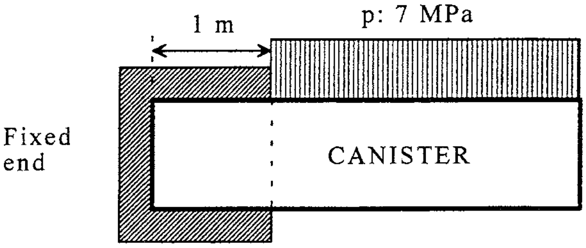
Bounding calculations must be carried out for three cases. These are easy to calculate, but not directly applicable since the degree of restraint and pressure differences are exaggerated. If the canister does not handle these cases successfully, more detailed calculations should be done.



Case 3 The canister is rigidly fixed on both end surfaces and along one-tenth of the length of the cylindrical surface nearest the ends. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.



Case 4 The canister is supported by a contact one-tenth of the length of the cylindrical surface from the ends. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.



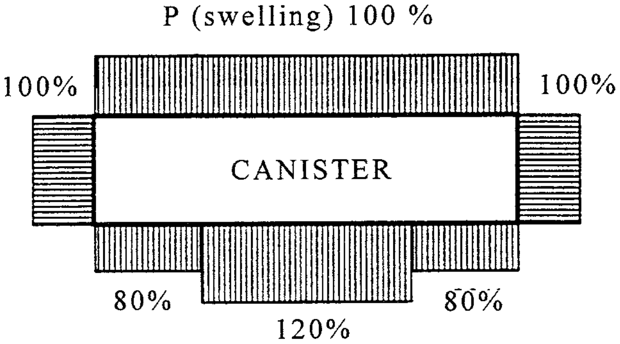
Case 5 The canister is rigidly fixed on one end surface and 1 m along the cylindrical surface nearest this end surface. An evenly distributed horizontal load corresponding to fully developed bentonite swelling pressure (7 MPa) acts along one side of the remaining canister surface.

Load cases 3 to 5, which occur without water pressure, are to be regarded as extreme cases for which no extra safety margins are required.

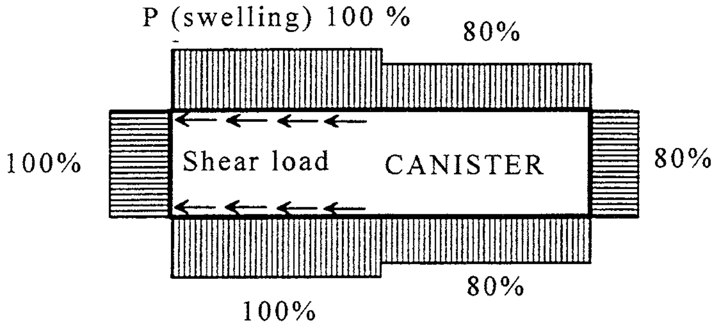
After water saturation

If the canister is tilted or inclined in the deposition hole, or if the rock is uneven, a permanent pressure disequilibrium can arise in the bentonite even after water saturation with full water pressure and ice load.

The canister should be designed for these loads with the customary safety margins.



Case 6A The swelling pressure is fully developed on one side of the canister's cylindrical surface and on the end surfaces. On the other side of the cylindrical surface, the swelling pressure is 20% elevated along the central half and 20% reduced along the remaining quarters at the ends of the canister.



Case 7A The swelling pressure is fully developed around the bottom half of the canister, while the swelling pressure is 20% lower around the top half. The resulting upward force, which results from the differences in pressure against the canister's end surfaces, is balanced by a shear force along the bottom half of the cylindrical surface.

Corresponding load cases, Cases 6B and 7B, where the swelling pressures are 50% higher and lower, respectively, are to be regarded as an extreme case for which no extra safety margins are required.

Case 8 Rock movements

The strength of the canister must also be evaluated for a rapid displacement of 0.1 m along a flatly dipping fracture. This load case is to be regarded as an extreme case for which no extra safety margins are required.

Case 9 Lithostatic pressure

In view of the dimensions of tunnels and deposition holes, any creep in the rock will not be able to be registered as increased load on the canister. Lithostatic pressure is thereby not a design-basis factor.

4.1.2 Impact on other barriers

Material impact on buffer and rock

The canister material and its corrosion products must not appreciably impair the performance of the buffer.

Dissolved substances from the canister material and its corrosion products must not chemically alter the buffer so that its swelling properties, hydraulic conductivity, and diffusion resistance are appreciably impaired in the buffer as a whole or locally by creating rapid transport pathways through the buffer. The same applies to gaseous corrosion productions.

The growth of corrosion products on the canister surface must not lead to a pressure build-up in the buffer that could threaten the mechanical integrity of the canister.

Impact of heat on buffer and rock

The surface temperature of the canister must not exceed 100°C.

Elevated temperature in conjunction with unfavourable groundwater chemistry can adversely affect the chemical stability of the bentonite buffer.

If extensive vaporisation of groundwater takes place during the initial phase in the repository before it is water-saturated, enrichments of precipitated substances, such as salts, can form on the canister surface. Then when the repository is saturated with water, the water chemistry in the immediate vicinity of the canister can be considerably more aggressive than otherwise foreseen. To prevent this, the canister is designed for a maximum outside temperature below 100°C.

This limits the canister's permissible surface heat flux, i.e., the ratio between the permissible decay heat of the fuel in the canister and the outside surface area of the canister.

Impact of radiation on buffer and rock

The canister's surface dose rate must not exceed 1 Gy/h.

The canister must provide sufficient radiation shielding to prevent radiation from altering the bentonite buffer or the water chemistry in the near field. This can occur by radiolysis of water or humid air prior to water saturation. The contribution of the radiolysis products to canister corrosion must be negligible in comparison with other corrosion during the life of the canister in the repository.

After deposition and before water saturation has occurred, the canister will stand in air with high humidity at a temperature of 90–100°C. Gamma irradiation of humid air leads to the formation of nitrogen oxides, which form nitric acid in contact with water. A simple method for carrying out a rough calculation of the quantity of nitric acid produced is shown in Marsh (1990). The rate of formation of nitric acid is given by:

$$\frac{d[HNO_3]}{dt} = \frac{G \cdot V \cdot \rho \cdot D_o}{A_v} \cdot e^{\frac{-0.693 \cdot t}{T}}$$

where G is the G value (molecules/eV), V the irradiated air volume(dm^3), ρ the density of the air (g/dm^3), D_0 the initial dose rate (eV/g·year), t the time in years, T the half-life in years of the radiation source and A_v Avogadro's number. If it is assumed that the gamma radiation source has a half-life of 30 years, G =2 molecules/100 eV, the air gap around the canister is 5 cm (V

= 825 dm^3) and $\rho = 1.184$ g/dm^3, then a production rate for nitric acid of 0.001 mol/year is obtained. This is a small amount that does not noticeably affect the life of the canister.

Nitrogen compounds such as nitrite and ammonia can give rise to stress corrosion cracking (SCC) in copper. The concentrations that could occur are very low and do not pose any risk of SCC, particularly as the copper canister before water saturation is largely free of tensile stresses on the surface.

The nitric acid production rate in the bentonite buffer can be estimated at 0.005 mol/year. Considering the calcite content in the bentonite, the bentonite will, with this low production rate, neutralise the acid. It will, therefore, not be dangerous for the canister.

After water saturation, radiolysis of the bentonite pore water leads to the formation of oxidants in the system. This has been investigated by King (1996), who draws the conclusion that for dose rates on the order of 1 Gy/h, no effects of radiation on corrosion can be expected.

Criticality

The fuel in the canister must not become critical.

The canister must be designed so that the fuel remains subcritical even if water should enter the canister. This influences the design of the interior of the canister in that the canister must either be designed so that the quantity of moderator (water) the canister can hold is limited, or suitable neutron absorbers must be incorporated in the canister.

Bottom pressure against bentonite

The canister must not sink through the bentonite.

The canister must be configured so that the bentonite layer underneath the canister is able to support the weight of the canister for a very long time.

4.2 SAFETY: OPERATION

4.2.1 Production

It must be possible to produce 200 canisters per year.

The canister must be designed so that it can be produced in serial production in compliance with specified quality requirements. This also imposes requirements on material selection and on fabrication and inspection methods.

The materials must be selected so that the capacity of subcontractors can guarantee that materials and canister blanks are always available in the necessary quantities. Wherever possible, the materials should be standard materials that can be delivered by several alternative manufacturers.

4.2.2 Handling

No foreseeable handling accidents shall lead to exposure of personnel to unacceptable radiation doses or of the plant to releases of radioactive material.

The canister must be able to be handled so that stresses and loads from foreseen accidents can either be absorbed by the canister itself or, where this is not possible, by suitably designed mechanical protections.

4.2.3 Transport

The canister must be able to be transported safety.

The canister must be able to be transported in purpose-built transport casks that meet customary requirements on radiation shielding, fire safety, and mechanical protection.

4.2.4 Retrieval

It must be possible to retrieve the canister from the deep repository for up to 40 years after emplacement.

The canister must be so designed that retrieval from the repository is possible. Any devices placed on the canister for retrieval purposes must not jeopardise the integrity of the canister in a long-range perspective in the repository. A retrieved canister shall be capable of being re-emplaced in a repository after a period of interim storage.

The canister shall be designed so that retrieval after 40 years is not hindered.

5 DESIGN

5.1 MATERIAL SELECTION

5.1.1 Chemical resistance

Chemical conditions in the repository

Over a period of more than 15 years, an extensive database on groundwater chemistry has been built up. Despite the fact that the data represent widely spread geographic regions of Sweden, they present a relatively consistent picture. Groundwater in granitic rock in Sweden is oxygen-free and reducing below a depth of 100 to 200 metres. The redox potential below this depth ranges between -200 and -300 mV on the hydrogen scale and the water has a pH ranging from neutral to mildly alkaline (7–9).

The range of variation is relatively limited when it comes to solute content as well. The chloride concentration in the groundwater can, however, vary within very wide limits, ranging from approx. 0.15 mmol/dm^3 to approx. 1.5 mol/dm^3. The chloride concentration is balanced by equivalent quantities of sodium and, particularly, in more saline water calcium. The concentrations of other substances are generally low. Moreover, reducing groundwaters have a typical concentration of dissolved sulphides of $1.5 \cdot 10^{-5}$ mmol/dm^3.

The chemical environment in the immediate vicinity of the canister is determined by the composition of the bentonite pore water. This is, in turn, determined by the interaction between the bentonite and the groundwater in the surrounding rock. Table 2 shows typical values for carbonaceous groundwater with a low chloride content equilibrated with bentonite.

Table 5-1. Typical values (mmol/dm^3) for carbonaceous groundwater with low chloride content equilibrated with bentonite.

Na^+	Cl^-	SO_4^{2-}	HCO_3^-/CO_3^{2-}	pH
90	2	30	3	9.3

The chloride concentration is not affected by the bentonite, which means that in the case of groundwaters with high chloride contents, equivalent values are obtained in the bentonite pore water with a corresponding increase in sodium concentration and also in calcium concentration. With the exception of chloride, the concentrations of other dominant anions will be determined for the foreseeable future by the interaction with the bentonite.

Chemical resistance of alternative canister materials

Resistance to corrosion can be achieved in several ways. The canister can be fabricated of a material that is not attacked by corrosion under the foreseen conditions; in other words, the material is immune to corrosion. Alternatively, resistance can be achieved by the formation of an impenetrable surface layer of corrosion products that protects the canister material against further corrosion. The material is then passive under the conditions in the repository. A third alternative is to fabricate the canister of a material that corrodes in a predictable fashion and give it a corrosion allowance that guarantees the desired service life in the repository.

Materials that are immune to corrosion are the noble metals and many ceramics. Passive materials include titanium, titanium alloys, stainless steels, and others. Canisters with corrosion allowances could be fabricated of low-alloy carbon steels.

Corroding materials, such as low-alloy carbon steels, have corrosion rates from a tenth of a micron per year up to several microns per year under repository conditions /Blackwood et al./. Over a period of 100,000 years, this corresponds to a corrosion loss of from several tens of millimetres up to several hundred millimetres. The uncertainties involved in extrapolating from laboratory data for corrosion rates measured during a period of months or years to thousands of years necessitate adding safety factors to the estimated corrosion attacks. In a conservative case with a corrosion rate of several microns per year and a safety factor of two to three, a canister wall thickness of up to 50 centimetres would be required. A canister with this wall thickness would be very heavy, 75 to 100 tonnes, and this would impair handling in the encapsulation plant and in the repository. The relatively high corrosion rate could also lead to a heavy build-up of corrosion products, which would affect other barriers in the near field mechanically and possibly also chemically.

Passive metals have a very low corrosion rate. Extrapolation of laboratory data show that general corrosion of, e.g., titanium would be very low even during long periods of time /Mattsson and Olefjord, Mattsson et al. 1990/. All passive metals are relatively new materials and very little is known about their properties over long periods of time. This is primarily true of the stability of the passive film, which is the basis of their corrosion resistance. Many of these metals, such as aluminium and titanium, are, in themselves, highly chemically unstable and would corrode very rapidly if the passive film were broken down. They are also sensitive to localised corrosion, particularly crevice corrosion, albeit to a varying degree.

Noble metals, which would be immune to corrosion under all circumstances that could occur in the repository, are really only gold and platinum. Neither of these metals is a practical alternative as a canister material.

Copper, on the other hand, has a wide stability range in oxygen-free water /Beverskog and Puigdomènech/, and oxygen-free conditions are expected during most of the repository performance lifetime. Dissolved sulphides in the groundwater change the situation, and copper can then corrode by formation of copper sulphide and hydrogen. The concentrations of dissolved sulphide in the near field of the canister are, however, very low and the corrosion attack on copper will, during long periods of time, be controlled by the availability of dissolved sulphides (Swedish Corrosion Institute 1978, Swedish Corrosion Institute 1983, Werme et al. 1992/.

Many ceramics, e.g. aluminium oxide and titanium oxide, are stable or corrode extremely slowly under repository conditions. On the other hand, these materials are brittle compared with metals and, therefore, sensitive to handling accidents. Bumps and impacts against the canister could lead to damage such that the requirement on the integrity of the canister could not be met. Even though development work is being done on ductile ceramics, these materials are scarcely realistic alternatives at present. Another disadvantage of ceramic canister materials is that they require high temperatures for sealing of the canister in the encapsulation plant. This increases the risks of fuel damage and release of radioactive substances.

Selection of canister material based on chemical considerations

Based on corrosion considerations, copper is ranked highest. The corrosion properties of copper are well known, and the occurrence of native copper and copper archaeological material several thousand years old makes it possible to verify models of general corrosion and pitting in varying environments over long periods of time.

The stability of copper in pure, oxygen-free water simplifies the models for long-term corrosion in the repository. After the oxygen has been consumed in the repository, after a few hundred years at the very most /Wersin et al. 1994A/, corrosion will be controlled completely by the supply of dissolved sulphide to the canister. This means that canister corrosion does not need to be described in reaction kinetics terms with the uncertainties that can exist with regard to corrosion rates and corrosion mechanisms over long time spans. Instead, the problem is reduced to describing diffusive transport of dissolved sulphides to the canister surface. This considerably increases the reliability of the predictions, since diffusive transport in porous media is well known and understood.

Corrosion of a copper canister in the repository environment has been studied thoroughly for more than 15 years, and an expected life of over 100,000 years can be achieved with adequate margins by a reasonable thickness of the canister wall /Swedish Corrosion Institute 1978, Swedish Corrosion Institute 1983, Werme et al. 1992, Wersin et al. 1994 B/.

The assessment of copper life in the repository could be influenced by bacterial corrosion if a biofilm of sulphate-reducing bacteria were to form on the canister surface. Experimental studies have shown, however, that with bentonite densities of 1800 kg/m^3 or higher, no sulphate-reducing bacteria can survive in the buffer or on the canister surface /Pedersen et al., Motamedi et al./.

Equivalent long-term assessments cannot be made with the same degree of reliability for any of the other alternative materials, with the exception of ceramics, even though it is not unlikely that other materials could also have sufficiently long lives in the repository. From a corrosion viewpoint, copper has, therefore, been selected as the material for canisters for spent nuclear fuel.

5.1.2 Mechanical strength

Mechanical conditions in the repository

The canister will be deposited in granitic rock at a depth of 400 to 700 metres under water-saturated conditions. This implies a hydrostatic pressure of 4 to 7 MPa. The design hydrostatic pressure is 7 MPa. The swelling pressure from the bentonite is added to this. The design swelling pressure is set at 7 MPa /Bäckblom/ These two pressure components are regarded as additive, and the design basis load is 14 MPa. The canister must be designed for this external pressure with the customary safety factor.

The safety factor has been chosen based on standard practice for steel structures and pressure vessels. Since the canister cannot be regarded as a conventional pressure vessel inasmuch as it is subjected to external pressure instead of internal pressure, special consideration has been given to regulations for steel structures. The choice of safety factor is discussed by Savås. The safety factor for the canister has been set to at least 2.5, which is to be compared with the minimum permissible safety factor of 2. The safety factor is supposed to cover uncertainties in material properties and fabrication, as well as uncertainties in the load in the deep repository. With a nominal load of 14 MPa, the canister should, thus, be designed for 35 MPa. During a glaciation, a load of up to 30 MPa (corresponding to 3,000 m of ice) may possibly be added. In order to cover also this case without extra safety margins (safety factor 1) the canister must designed for at least 44 MPa, which is then the design basis case.

Mechanical strength of alternative canister materials

The mechanical strength of a canister for spent nuclear fuel is largely dependent on the canister design. The canister can be designed so that the canister's own shell is capable of withstanding the external pressure. Alternatively, it can be designed so that the requisite mechanical strength is provided by a suitably designed inner structure that supports the outer shell. For fabrication-related and strength-related reasons, it is assumed that the canister takes the form of a cylinder with planar lid and bottom.

In order that a cylindrical shell with a reasonable wall thickness should be able to support the load of groundwater pressure and bentonite swelling pressure with the desired safety factor, the material must have a yield strength of over 250 MPa (see the design calculations in /Savås/). Based on corrosion considerations, copper has been deemed to be the most suitable canister material; however, pure annealed copper has a yield stress of approximately 50 MPa. This means that a canister of pure copper cannot be made self-supporting. The strength of the copper can be increased by additions of alloying elements. Even though certain copper alloys, such as copper-nickel, have better corrosion resistance than copper under oxidising conditions, the stress levels in a self-supporting copper canister in the repository can increase the risk of stress corrosion cracking. The assessment of the material's corrosion properties over very long periods of time is also complicated by the fact that the copper material is rendered less noble by alloying. In the case of certain alloys, there is also a risk that the alloying elements will, in the long time perspective, be leached out, since they are less noble than copper. If copper is chosen as the canister material, the canister must be designed so that the necessary strength is provided by an inner supporting structure. Furthermore, the ductility of the copper material shall be sufficient to allow any strains that may occur in the repository when the copper canister is deformed against the inner pressure-bearing component.

The necessary strength of a copper canister can be achieved by completely filling the void inside the canister. The feasibility of achieving this by filling the canister with lead or fabricating a solid copper canister by hot isostatic pressing was discussed in KBS-3. As an alternative to these methods, the necessary strength can be achieved by furnishing the canister with a pressure-bearing insert of a material with sufficiently high strength.

Selection of canister material based on mechanical considerations

Filling the canister with molten lead or fabricating the canister by means of hot isostatic pressing requires subjecting the canister after loading with fuel to elevated temperatures and, in the case of isostatic pressing, to high pressures as well. These options increase the risk of accidents in the encapsulation plant and have, therefore, been regarded as less suitable canister designs. The alternative of giving the copper canister the necessary mechanical strength by furnishing it with an insert of sufficiently strong material is, therefore, ranked highest.

5.1.3 Choice of copper grade

From the corrosion viewpoint, pure oxygen-free copper should be used. The requirements on mechanical strength are subordinate, but for the alternative with a load-bearing insert it will be necessary to have a radial gap of a millimetre or so between the insert and the copper shell for fabrication-related reasons. When load is applied, the copper shell will deform until it obtains support against the insert. This requires selection of a copper grade with sufficient ductility, including creep ductility. Creep testing has been performed on alternative copper grades, and the results to date show that pure oxygen-free copper as per ASTM UNS C10100 (Cu-OFE) or EN 133/63: 1994 Cu-OF1 exhibits unsatisfactory creep ductility at elevated temperature (200 to 250°C) /Henderson and Sandström/. Other copper materials, particularly phosphorus- and silver-alloyed copper, have proved not to have the limitations of pure oxygen-free copper in this respect /Henderson and Werme, Lindblom et al./.

After considering all other requirements apart from corrosion resistance, the material for the copper canister has been chosen to conform to the specifications of ASTM UNS C10100 (Cu-OFE) or EN133/63: 1994 Cu-OF1. Table 5-2 shows the composition of these copper grades.

Table 5-2: Composition in ppm of oxygen-free copper as per European and American standard.

Alloy	Cu (%)	Ag	As	Fe	S	Sb	Se	Te	Pb
C10100	99.99[1]	25[2]	5[2]	10[2]	15[2]	4[2]	3[2]	2[2]	5[2]
Cu-OF1		25[2]	5[3]	10[4]	15[2]	4[2]	2[2]	2[5]	5[2]

[1] Including silver

[2] Maximum permissible concentrations

[3] Σ As + Cd + Cr + Mn + Sb max. 0.0015% (15 ppm)

[4] Σ Co + Fe + Ni + Si + Sn + Zn max. 0.0020% (20 ppm)

[5] Σ Bi + Se + Te max. 0.0003% (3 ppm), Σ Se + Te max. 0.00030% (3,0 ppm)

In addition to these specifications, the oxygen content of Cu-OF1 must be such that hydrogen embrittlement cannot occur. The following maximum concentrations of other elements apply to C10100: Bi: 1ppm; Cd: 1 ppm; Mn: 0.5 ppm; Hg: 1 ppm; Ni: 10 ppm; O: 5 ppm; Sn: 2 ppm; Zn: 1 ppm.

In addition to the requirements on the copper grade that are related to corrosion properties, requirements are also made related to the fabrication of the canister and the necessary mechanical properties (also discussed in 5.1.2). These requirements are: H < 0.6 ppm, S < 8 ppm, P 40–60 ppm and grain size 180–360 µm. Grain size is measured according to ASTM's comparison method E 112. Table 5-3 gives the reasons for the requirements on analysis, grain size and mechanical properties.

Electrolytic copper is normally very pure. Impurities and valuable trace substances are collected as sludge on the bottom of the electrolysis tank. The conditions during smelting and casting then determine the oxygen content of the copper (and the phosphorus content if phosphorus-deoxidised copper is produced). The impurities influence the copper's recrystallisation temperature even at concentrations of less than 10 ppm /Sundberg/. Mechanical properties such as tensile strength and ductility are generally not affected by small levels of impurities, but it is likely that the impurities that cause elevated recrystallisation temperatures at concentrations of only 1 to 10 ppm indicate grain boundary segregation and, thereby, a risk of weakness at the grain boundaries. In view of this, it is likely that sulphur, bismuth, selenium and tellurium, which have low solubility in copper, are the most detrimental.

Table 5-3. Reasons for the requirements on analysis, grain size and mechanical properties

Requirement	Reason
O < 5 ppm	Risk of poorer weldability at higher concentrations.
H < 0.6 ppm	Adverse impact on mechanical properties at higher concentrations.
S < 8 ppm	Higher levels have an adverse impact on mechanical properties due to copper sulphide at the grain boundaries.
P 40 - 60 ppm	Phosphorus concentrations of this magnitude mitigate the effect of sulphur impurities, increase creep ductility, raise the recrystallisation temperature and have little impact on weldability.
Grain size < 360 μm	At this grain size, a resolution is obtained in ultrasonic testing that is comparable to radiography of 50 mm thick copper.
Elongation at failure > 40% RT - 100°C	The copper canister will be deformed about 4% in the repository[1]
Elongation at creep failure > 10% RT - 100°C	The copper canister will be deformed about 4% in the repository[1]

[1] See calculations by Cakmak.

Bismuth concentrations of 10 ppm can give rise to brittleness in the temperature range 450–600°C.

SKB's investigations have shown that the creep ductility of copper can be greatly affected by even small concentrations of sulphur /Henderson et al. 1992, Henderson and Sandström/. Auger analyses indicated high levels of sulphur (8 to 13 at-%) at the grain boundaries. Takuno et al. have confirmed this. In the same way as Henderson et al. (1992), Takuno et al. found that sulphur segregation to the grain boundaries is influenced by phosphorus and oxygen.

Phosphorus also influences the recrystallisation temperature, but since the solubility of phosphorus is relatively high another mechanism is probably involved.

It is probable that the reduced creep ductility observed in the temperature range 200 to 250°C is caused by sulphur segregation to the grain boundaries, leading to embrittlement. Phosphorus apparently alters this property, but the mechanism is still not understood.

5.1.4 Impact on other barriers in the deep repository

Material impact

Passive materials such as titanium and titanium alloys are protected against corrosion by an impenetrable and insoluble surface layer. As long as the material remains passive, the chemical impact on buffer and rock will be negligible. The same applies to the mechanical impact, since the very slow growth of corrosion products leads to a very slow pressure build-up in the buffer.

Corroding materials with corrosion allowance, such as iron and steel, will give rise to appreciable quantities of corrosion products. Since the density of the corrosion products is lower than that of the original material, this will lead to a pressure build-up in the near field of the canister. If the corrosion products are to some extent soluble, for example as Fe^{2+} for iron or steel, a chemical impact on the bentonite cannot be ruled out, either.

The solubility of copper sulphide, which is a corrosion product of copper under reducing conditions, is extremely low. A chemical impact on buffer and rock can, therefore, be ruled out. Given the extremely low corrosion rate of copper under reducing conditions in the repository environment (see below), no mechanical impact on the near field will arise, either.

Thermal impact

Thermal impact on bentonite and rock is not related to material selection but, rather, primarily to canister design.

Radiation impact

The impact of radiation on bentonite and rock is not related to material selection but, rather, primarily to canister design.

Criticality

The question of criticality in the repository is not related to material selection but, rather, primarily to canister design.

Bottom pressure against bentonite

The pressure of the canister bottom against bentonite is not related to material selection but, rather, primarily to canister design.

5.2 CANISTER DESIGN

5.2.1 Schematic design

The canister will be designed with an outer layer of copper (overpack) for corrosion protection. To provide the necessary mechanical strength, the copper layer will be supported by a pressure-bearing insert. Size has been determined by the requirement that each canister should have room for 12 BWR assemblies or 4 PWR assemblies /Pettersson/.

5.2.2 Copper layer of the canister

Structural design

Corrosion protection

From corrosion point of view, the wall thickness of the copper layer must be at least 15 mm.

The copper layer provides the corrosion barrier for the canister. It shall provide adequate protection against corrosion for a long time after water saturation. It shall also provide protection against atmospheric corrosion before disposal and after disposal before water saturation. No known forms of corrosion attack shall be able to lead to a shorter canister service life than 100,000 years. The outside of the copper canister will corrode in the repository from:

- oxygen retained in the repository before water saturation.
- oxygen supplied from the buffer or from the groundwater via the buffer.
- sulphide supplied from the buffer or from the groundwater via the buffer.

Corrosion under oxic conditions

In pure water in the presence of oxygen, copper will oxidise to Cu_2O or CuO, depending on the redox potential. In the presence of ligands, hydroxi-sulphates, hydroxi-carbonates or hydroxi-chlorides may form. These may also form under atmospheric corrosion.

Corrosion before deep disposal: Mattsson (1997) has assessed the external corrosion of copper canister awaiting deep disposal and during the initial stage of disposal. During a possible intermediate storage, awaiting disposal, the canisters will be subject to atmospheric corrosion. The storage is assumed to take place in normal city atmosphere and if the surface temperature on the canisters were kept at 20°C, the estimated corrosion rate would be in the interval 0.006 to 0.027 μm per year. If the surface temperature would be 90°C, the corrosion rate is estimated to be 100 times higher. The assessment is based on an assumed doubling of the chemical reaction rate for a temperature increase of 10 degrees. If the corrosion takes place in dry air, a layer of mainly copper oxide will be formed on the canister surface. A corrosion attack of a few micrometres before disposal will not affect the service life of the canister in the repository.

Corrosion under aerobic conditions during the phase of bentonite saturation: After disposal and before water saturation it is possible that the canister can be in contact with air at a temperature of 90°C. Based on corrosion rates for outdoor exposure of copper to city atmosphere, Mattsson estimates the corrosion rate to be as large as 100 to 300 μm per year if the supply of oxygen is not limited. The corrosion attack is expected to be evenly distributed over the copper surface since pitting corrosion will not be possible under these conditions. The total corrosion attack can be estimated from mass balance considerations. The volume in the deposition tunnel and in the deposition hole is 56.5 m^3 per canister. The porosity in the bentonite and the backfill material can pessimistically be estimated to be 40 %. If all of this porosity consisted of air, the amount of oxygen per canister would be 4.5 m^3 or approximately 200 mol of O_2. Assuming that Cu_2O is formed as corrosion product, 800 mol of copper or 50 kg will be oxidised. This corresponds to a largest possible corrosion attack of 300 μm evenly distributed over the canister. In reality the corrosion will be considerably smaller since the transport of oxygen to the canister will be limiting.

Copper corrosion after water saturation; oxygen corrosion: After water saturation oxygen will still be present in the surroundings of the canister. This oxygen is consumed partly by reaction with the copper canister and partly by reactions with minerals in the bentonite buffer. When the oxygen has been consumed the reducing conditions, present before the repository was built, will be re-established. The time for this is estimated to 10 to 300 years /Wersin et al., 1994A/. During a shorter period of at the most a few hundred years after disposal in the repository when oxygen is present, the maximum corrosion depth is very pessimistically estimated to approximately 2 mm, but will probably only be a few micrometres /Wersin et al., 1994B/. In the former case an unrealistically high pitting factor of 100 was used. In the latter case a pitting factor of 5 was used. The total corrosion attack will be determined by the amount of accessible oxygen. It should be noted that it is the trapped amount of oxygen, which causes the corrosion both before and after water saturation. The maximum corrosion attacks for these two cases shall, therefore, not be added.

Corrosion under oxygen-free conditions

Copper corrosion after water saturation; sulphide corrosion: In the absence of oxygen, copper is immune to corrosion in pure water. For further corrosion to occur the water must contain dissolved substances, which can affect the immunity of copper. For the conditions in a repository, dissolved sulphide and very high concentrations of chloride at low pH are the only ones conceivable. Since deep groundwaters are neutral or slightly alkaline and the bentonite buffer counteracts acidification, dissolved sulphides are in practise the only corrosive substances that can react with the copper canister after the oxygen in the repository has been consumed. The corrosion products will then be Cu_2S or CuS and hydrogen gas. At the disposal depth, the groundwater has very low sulphide concentrations, considerably less than $5 \cdot 10^{-5}$ mol/dm^3, and the solubility of the sulphide minerals present in the bentonite are, at the most, similar. This means that the access to and supply of sulphides from the groundwater and the buffer will control the corrosion of the copper canister due to sulphide.

In the same way as for oxidising conditions Wersin et al. (1994B) have estimated the extent of the corrosion with a very pessimistic assumption and for the most probable case. In the former case the corrosion depth will be 2 mm, but will probably amount to less than one tenth of a millimetre.

Influence of temperature: The temperature in the repository during the oxidising phase will reach a maximum temperature of 90°C on the copper surface. The temperature increase from 20°C to 90°C increases the corrosion rate for copper by a factor of one hundred based on the simple assumption that the corrosion rate doubles with a temperature increase of ten degrees. This is of secondary importance since the diffusion of reactants is rate controlling and the diffusivity is far less affected by temperature. The effect of temperature on the chemical equilibria for the corrosion reactions is negligible for the temperature interval that applies to the repository.

Influence of chemical changes during glaciations: It has been discussed whether present chemical conditions at greater depth in Swedish bedrock are going to be stable over long times. The Fennoscandian shield has been subjected to several glaciations and the question has arisen whether in conjunction with melting of the inland ice, oxygen-containing water could penetrate deep into the bedrock. In a repository this could lead to increased corrosion of the canisters. There is, however, no unequivocal evidence that oxygen-containing water has penetrated deep into the bedrock. It cannot, however, be completely excluded that oxygen-containing water from time to time penetrates crush zones and fractures with high conductivity.

The oxygen content of the water can be estimated to be 10 mg/l. If one assumes that a 100,000 year period has in total 5,000 years of ice melting when oxygenated water penetrates the repository with a pessimistically high equivalent flow of 10 litres per year, a total of 400 g of copper will corrode. This corresponds to 26 μm for uniform corrosion. With a pitting factor of 5, which was used in KBS-3, the deepest pit would 130 μm.

Stress corrosion cracking: Stress corrosion cracking is a process that could rapidly lead to canister penetration. For initiating propagation of stress corrosion cracks, a combination of unfavourable chemical conditions and tensile stresses in the material will be required. The risks for stress corrosion cracking can be minimised by choosing a disposal site with favourable chemical conditions and designing the canister in such a way that tensile stresses at the surface of the canister are avoided to the largest possible extent. The risks for stress corrosion cracking will, thereby, not be related primarily to the thickness of the material, but more to the design of the canister. Studies indicate that stress corrosion cracking for the copper qualities that are of interest, is improbable for the foreseen disposal conditions after reducing conditions are established in the immediate surroundings of the canister /Benjamin et al., Rosborg and Svensson/.

General assessment: Even with very pessimistic assumptions, the maximum corrosion attack during 100,000 years will not exceed 5 mm, and will probably not exceed more than a few tenths of a millimetre.

The uncertainties in assessments for long time periods are large and the copper thickness must be chosen with a suitable safety factor. Large safety factors are already inherent in the assessments of the extent of the corrosion during the different phases in the history of the repository; therefore, it is reasonable to use a safety factor of the same magnitude as was used for the design for mechanical loads. This would lead, from corrosion point of view, to a minimum acceptable wall thickness of 15 mm.

Importance of copper thickness

Even if 15 mm is a suitable minimum wall thickness from a corrosion viewpoint for ensuring long-term safety, other factors also influence the choice of canister thickness. These factors are:

- fabrication of copper cylinder.
- handling of copper cylinder.
- sealing method.
- inspection method.
- handling of filled canister.

The influence of these factors will be further investigated and presented in a special report, but the following can be said in summary.

The fabrication of copper plates is simplified if their thickness is reduced. The reduction ratio in rolling can be greater than for thicker plates, and better control is obtained over the metal's microstructure. Thinner walls lead to reduced mechanical stability of the copper cylinder. Excessively thin walls can cause problems in machining, stress relieving and transport of the canister.

Sealing of the canister and welding of copper are simplified by thinner material. Down to 30 mm, electron beam welding is deemed to be the most realistic alternative. At a wall thickness of less than 40 mm, electron beam welding without vacuum might be possible; however, this requires further development work estimated to take 1 to 2 years. At wall thicknesses of less than 20 mm, welding by means of conventional methods such as TIG can be practical; however, this requires preheating of the copper to several hundred degrees. Conventional welding could be done at even greater material thicknesses, but is not deemed to be a practical alternative since it leads to long welding times and probably unacceptable heating of the canister. Friction welding is a possible alternative, but requires large equipment and relatively extensive development of both technique and equipment. At the canister thicknesses being considered, electron beam welding is the only proven method available today.

Both ultrasonic and radiographic testing are simplified by the choice of thinner material. In the case of ultrasonic testing the gains are more marginal, since the microstructure of the weld dominates the background noise in the ultrasonic signal. In the case of radiography, ways to reduce the x-ray energy could simplify the radiography equipment, the requirements on radiation shielding, as well as the costs of the equipment. This requires further study.

After considering together the demands on corrosion resistance, mechanical stability, microstructure in the material, fabrication techniques and non-destructive testing, a wall thickness of 30 mm is a suitable choice.

5.2.3 Pressure-bearing component

Structural design

Design for pressure

The canister's pressure-bearing component must be designed for an external pressure of 44 MPa, se section 5.1.2. Low-alloyed steels have a yield stress in the range 200–330 MPa at 100°C. The necessary compressive strength against plasticising for a self-supporting cylinder of these materials can be obtained at reasonable wall thicknesses (about 50 mm) without limiting the choice of canister dimensions /Savås/.

As an alternative to the self-supporting insert, an insert with a supporting inner structure can be used. See the schematic diagram in Figure 5-1 for the design for BWR fuel. The canister for PWR fuel differs in the configuration of the cross-section of the insert, as shown in Figure 5-2. The canister is fabricated so that the fuel assemblies can be placed in individual channels separated by partition walls. This insert can be cast in nodular iron (SS 0717), steel (SS 1306) or possibly bronze /Werme and Eriksson/. The structural design of such an insert is governed more by casting-related considerations than by designing against pressure. The thickness of partition walls and the outside diameter of the insert are determined by the casting properties of the metal and by the requirement that criticality must be avoided if water should enter the canister. Of the metals in question, nodular iron has the best castability and is therefore chosen as a reference material. Nodular cast iron SS 0717-00 has a density of 7100 kg/m^3 and mechanical properties according to Table 5-4.

Table 5-4: Mechanical properties of SS 0717-00 at 20°C and 100°C .

Properties	At 20°C	At 100°C
Yield strength (MPa)	250	235
Tensile strength (MPa)	400	375
Elongation at failure (%)	22	22
Young's modulus (GPa)	170	162
Poisson's number	0.3	0.3

Bounding calculations for the canister insert

Cases 1&2 The critical pressure for a canister configured according to Figure 5-2 was calculated to be 81 MPa for the BWR version and 114 MPa for the PWR version /Ekberg/. This design also gives a margin of approximately almost 40 MPa for the design basis case. Even though the details of the canister design may be modified for production-related reasons, the conceptual design provides adequate safety margins. In the BWR case, the spacing between the channels for the fuel assemblies was set at 50 mm. If the spacing was reduced to 30 mm, the corresponding load was at least 60 MPa.

Cases 3-7 The load cases were calculated according to the manual. The following input data were used for the BWR version:

Second moment of area I: 0.02803 m^4
Section modulus W: 0.05901 m^3

The results for load cases 3–6 are given in Table 5-5.

Table 5-5: Bending moment and bending stress for load cases 3-6

Load case	Maximum bending moment	Maximum bending moment (MNm)	Maximum bending stress (MPa)
3	$4/75 \cdot pDL^2$	7.2	122
4	$2/25 \cdot pDL^2$	10.8	183
5	$7.562/25 \cdot pDL^2$	40.7	690
6A	$1/80 \cdot pDL^2$	1.7	29
6B	$1/32 \cdot pDL^2$	4.2	71

Where: p is the bentonite swelling pressure (7 MPa)

D is the outside diameter of the cylinder (0.95 m)

L is the length of the cylinder (4.5 m)

The yield strength (240 MPa) is not reached in cases 3, 4 and 6, while case 5 leads to unacceptable load on the canister insert. FEM calculations have been carried out for cases 4 and 5, in which the material properties of the bentonite have also been taken into account /Börgesson and Hernelind/. Maximum tensile stresses in the canister insert were then found to be below 55 MPa.

The load cases 7A&B are load cases where the whole load may be borne by the outer copper layer. The unbalanced force between the ends of the canister must be borne by the axial friction between copper and bentonite. The unbalanced force is:

$$\Delta F = \Delta p \cdot \pi \cdot D^2/4$$

where ΔF is the unbalanced axial force

Δp is the pressure difference between the ends of the canister (20% and 50% of 8 MPa, respectively.)

D is the outside diameter of the canister (1.05 m)

Case 7A: $\Delta F = 1.2$ MN

Case 7B: $\Delta F = 3.0$ MN

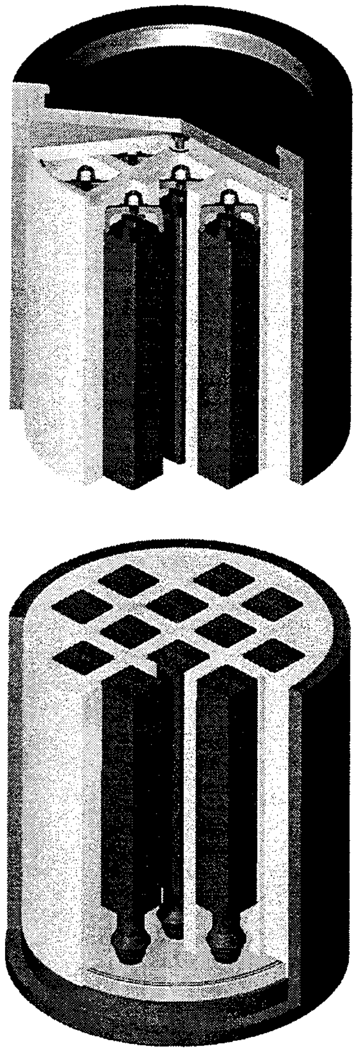


Figure 5-1. Exploded drawing of canister for spent nuclear fuel. Version for 12 BWR elements.

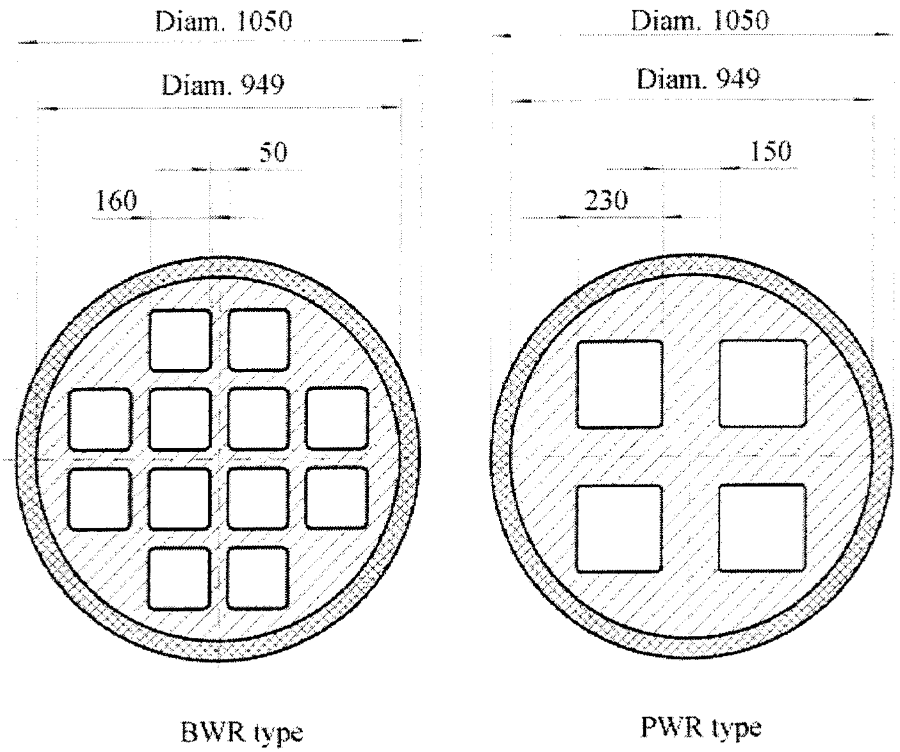


Figure 5-2. Cross-sections of canister and canister insert for BWR and PWR fuel.

If the friction between the copper shell and the insert is disregarded, this force will be absorbed by the copper shell, corresponding to an axial stress in the copper wall of 7.7 and 19.3 MPa, respectively. These are low stresses compared with the yield strength of 45 MPa. The resulting shear stresses are considerably lower.

Case 8 The impact of rock movements on the mechanical stability of a self-supporting copper-steel canister has been investigated by Börgesson. The canister studied is equivalent to that analysed by Savås and the limit load lies in the range 45 to 55 MPa. This is much lower than in the case of the copper canister with cast insert. The calculations, can therefore, be regarded as conservative to some extent. Börgesson found that rock movements on the order of 0.1 m do not lead to canister failure. The strains in the copper shell were low, below 2.5%.

Börgesson also tried to calculate the creep deformation after the shear movement in the rock. A conservative estimate showed that the deformation during a period of up to 100,000 years could lead to strains of approximately 6% on the cylindrical portion of the copper canister and up to 36% in the lid. The possibility that a very early shear movement in the rock might shorten the life of the canister can, therefore, not be ruled out. In view of the very low probability of such events, the risks of canister penetration are, nevertheless, judged to be very small.

5.2.4 Structural design of canister with insert

Besides being designed for resistance to external corrosion and for mechanical strength, the canister must also be designed with respect to internal corrosion, radiation protection, criticality, and pressure of the canister bottom on the bentonite buffer.

Internal corrosion

The canister insert will be exposed to internal corrosion if the void in the insert is filled with air. The total void volume in the BWR version is approximately 1.3 m^3. The fuel assemblies occupy an estimated 30% of this volume. The remaining void volume is then 1 m^3, 20% of which consists of oxygen. This is equivalent to 9 mol, which, if it is consumed by reacting with the cast iron and produces FeO (conservative assumption), would result in a corrosion depth of 4 μm.

At room temperature, air with 100% humidity contains 25 g of water per m^3. the total internal insert area is 34 m^2. If the water in the air is consumed, like the oxygen, by formation of FeO, this would cause a corrosion loss of 0.3 μm. These corrosion depths cannot jeopardise the integrity of the canister in the long term.

The risks of internal corrosion caused by the effects of irradiation of humid air must also be taken into consideration. If the same formula is used as in section 4.1.2, the result is that at a dose rate of 300 to 500 Gy/h, all water would be consumed in the production of nitric acid after 3 to 6 years. The quantity of nitric acid formed is then 2.8 mol. The nitric acid could cause SCC if it condenses on areas with tensile stresses on the canister insert.

During the early phase after sealing and deposition, the temperature of the insert nearest the fuel will be over 150°C. At that temperature there is no water in liquid form in the canister and the relative humidity is too low for a film of water to form on the metal surface, even if water has been transferred to the canister enclosed in a fuel rod. (The largest quantity that could be transferred in this way in isolated cases is estimated to be 50 g, equivalent to the void volume in a fuel rod.) For water film to form would require a relative humidity of approximately 40%. Under these conditions, nitric acid is not stable but decomposes to NO_2, which is the dominant radiolysis product in dry air /Reed and Van Konynenburg, 1991A, 1991B/. In order that the water and oxygen in the canister are not consumed during the time it takes for the temperature to fall so that water/nitric acid can condense, the corrosion rate must be extremely low. The risk of damage to the canister insert due to SCC should, therefore, be very small, particularly since the tensile stresses that can arise are small and local /Ekberg/.

If the risk of SCC is, nevertheless, deemed to be unacceptable, the air in the canister can be replaced with an inert gas. In this way the quantity of nitric acid that can be produced can be further limited /Henshaw/.

Radiation shielding

In order to meet the requirement on a maximum permissible surface dose rate of 1 Gy/h, the canister must have a minimum total wall thickness of about 100 mm /Håkansson 1995, Håkansson 1996, Lundgren/, divided between the insert and the copper shell.

Thermal load on bentonite

The maximum permissible canister temperature of 100°C is lower than the maximum permissible temperature in the bentonite buffer (130°C). A harmful thermal load on the bentonite can be ruled out.

For each set of heat transfer data for bentonite buffer and rock, the surface temperature on the canister is a function of the decay heat in the fuel and the area of the canister. The requirement of a maximum surface temperature of 100°C sets a limit on the permissible surface heat flux (W/m^2) from the canister. The length of the canister is determined by the length of the fuel assemblies, while the diameter can be varied more freely. The volume in the canister and, thereby, the quantity of fuel that can be encapsulated varies with the cube of the diameter, while the canister area varies with the square of the diameter. This means that there is an upper limit at which the inner volume of the canister can be utilised optimally. If the total decay heat of the encapsulated fuel is too high, the canister must be oversized in order to keep the surface heat flux within permissible limits.

The importance of the canister dimensions for the surface temperature of the canister will be explored in a separate report /Pettersson/, but the results so far indicate that a canister with 12 BWR assemblies or 4 PWR assemblies is close to the optimal size for the decay heats that are predicted for the fuel at encapsulation.

Criticality

With a canister insert in the form of a self-supporting cylinder, the void volume in the canister will be such that there is a risk of criticality if water enters the canister. This can be counteracted by reducing the void volume, for example by filling the canister with a powder or granulate. This complicates canister handling during encapsulation. In the design with the cast insert, the partition walls fill this function and prevent criticality even if the canister should be filled with water provided the fuel is credited with a relatively low burn-up /Efraimson/.

6 REFERENCE CANISTER

The design of the reference canister for BWR fuel is illustrated by Figure 4. It consists of an insert of cast nodular iron with a 50 mm spacing between the fuel channels and 50 mm minimum metal cover to the periphery. The wall thickness of the copper canister is 50 mm to satisfy the requirement of 100 mm total metal cover for radiation shielding. A more detailed description is provided in Werme and Eriksson.

The inner container or insert is cast with an integral bottom of nodular iron according to Swedish Standard SS 140717-00. The fuel channels are constructed of hot-drawn square tubes, 156x156 mm, with 10 mm material thickness in the form of a rack, which is then embedded in cast nodular iron. The spacing between nearby tubes in the rack is 30 mm. The weight of a canister with fuel is about 25 tonnes in the BWR version and about 27 tonnes in the PWR version.

The function of the inner container is to support the external load in the deep repository, but also to guarantee integrity during sealing of the copper shell. This integrity is achieved by closure of the lid with a bolt in the centre with O-ring seals of, for example, Viton. The insert is placed inside an outer canister or shell (overpack) of copper. To enable the two components to be put together, the insert has an outer diameter that is 3.5 mm smaller than the inner diameter of the copper shell. This clearance guarantees a maximum strain in the copper of less than 4% when the copper shell is pressed against the insert as a result of the water pressure and the bentonite's swelling pressure build-up /Cakmak/. This value is met by the requirements on the ductility of the copper material.

The copper canister is fabricated either in the form of two tube halves formed from rolled plate that are then welded together with two longitudinal welds, or of seamless extruded tubes. The longitudinal welds are made by conventional electron beam welding.

The design of the lid and bottom has been chosen so that it is possible to examine the weld by digital radiography and by ultrasonic testing. The recess in the lid and bottom make it possible to position the detectors for digital radiography so that the joints can be x-rayed in the welding direction. This design also keeps the weld at a safe distance from the top and bottom of the insert, which are the areas where the greatest strains occur in the copper canister when peak water pressure and swelling pressure develop in the repository /Cakmak/.

The design of the canister bottom may conflict with the requirement that the bentonite buffer must be able to support the canister, since it may be difficult to design the buffer so that the entire bottom surface is supported by the buffer immediately after emplacement. Emplacement tests in the Äspö Hard

Rock Laboratory shall determine whether and in what way the bottom design may need to be modified.

The recess in the lid also makes it possible to make a flange on the inside of the recess that can be used to lift and handle the canister after sealing in the encapsulation plant and in conjunction with shipments to and handling in the repository. Scoping calculations of the strength of the lifting flange have been carried out by Lenstad and Kalbantner. The calculations are based on a canister weight of 25 tonnes, which has been multiplied with a partial safety factor for dynamic load of 1.3 and a factor for unevenly distributed load on the lifting device's grippers of 1.5. The calculations showed that local plastic deformation will occur. Since the lid will only be lifted a few times, the risk of fatigue is judged to be small.

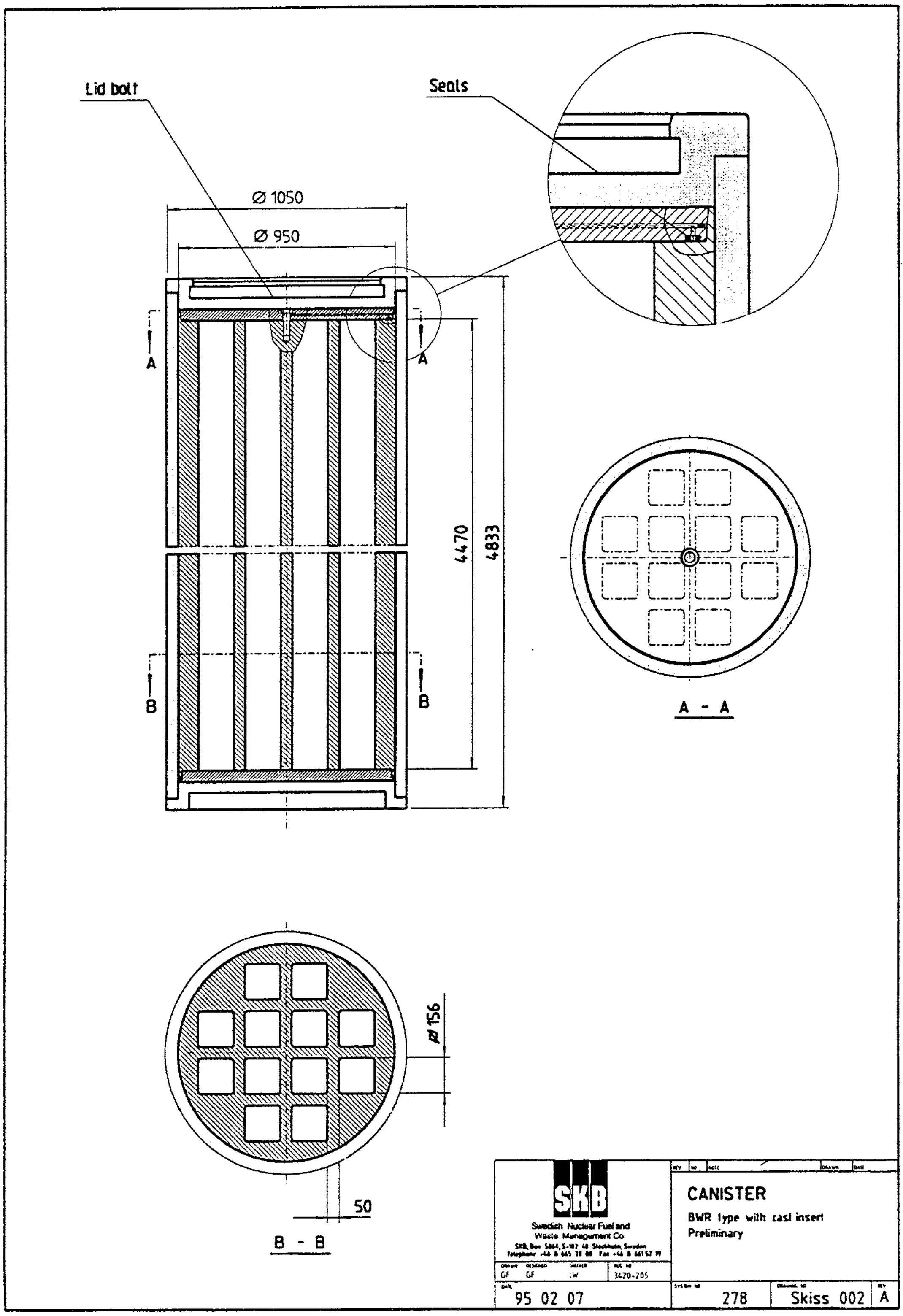


Figure 6-1. Dimensional drawing of canister for spent nuclear fuel. Version for 12 BWR assemblies.

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APPENDIX 1: DESIGN GUIDE FOR CANISTER

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GENERAL

Four factors influence the stresses in the canisters and thereby the canister design:

1. Hydrostatic pressure under glacial conditions.
2. The swelling pressure of the bentonite, which can be uneven due to uneven wetting.
3. Pressure increments due to rock displacements along fracture planes.
4. Pressure increments due to creep-induced shrinkage of the emplacement hole.

HYDROSTATIC PRESSURE

The water pressure will probably build up to full piezometric pressure within a few tens of years following repository closure. Emplacement at a maximum depth of 700 m results in a pressure of no more than 7 MPa.

Glaciation may result in an ice sheet about 3 km thick within the next 100,000 years. Deep crevices may reach down do the bottom surface of the ice, which may be separated from the ground surface. Continuous water columns with a height of 3.7 km may, therefore, form down to the repository depth of 0.7 km, where the water pressure may therefore be as much as 34.5 MPa.

SWELLING PRESSURE OF BENTONITE

Magnitude of swelling pressure

The swelling pressure exerted by the buffer is a function of the porosity (or the dry density) and the degree of saturation. The swelling pressure does not reach its peak until full water saturation. The swelling pressure at full water saturation has been calculated for the following three cases:

1) Highest possible density (lowest porosity) after swelling-out into gaps, assuming that compaction has been done under the most advantageous conditions for achieving high density. If compaction has been done at 500 MPa and the natural water content for MX-80 (w=10%), a porosity of about e=0.38 can presumably be achieved (extrapolated from measurement data reported by Johannesson et al. (1995)). Blocks of this type are placed around the canister with a 10 mm gap to the canister and a 50 mm gap to the rock. The latter gap is filled with pellets with the same porosity to a "pellet porosity" of n=0.25. This gives the following mean values, which have been calculated from the measurement results reported by Börgesson et al. (1995):

e=0.451

ρ_d= 1920 kg/m^3 (dry density)

ρ_m= 2230 kg/m^3 (density at water saturation)

s ≈ 100 MPa (swelling pressure)

Upward swelling has been assumed to be small, since this assumption gives the highest swelling pressure. These values are probably at the limit for what is technically feasible.

2) Same as 1) but with compaction at high water saturation. Compaction has been assumed to take place at 500 MPa and w=17%. e=0.5 can be expected to be reached. This gives the following mean values:

e = 0.577

ρ_d= 1760 kg/m^3 (dry density)

ρ_m= 2130 kg/m^3 (density at water saturation)

s ≈ 30 MPa (swelling pressure)

3) Here compaction has been done at the standard pressure 100 MPa at w=17%. e=0.57 can be expected to be achieved in blocks and pellets under these circumstances. Pellet porosity is assumed to be n=0.33. This gives the following mean values:

e= 0.678

ρ_d= 1660 kg/m^3 (dry density)

ρ_m= 2060 kg/m^3 (density at water saturation)

s ≈ 13 MPa (swelling pressure)

4) If 7 MPa is assumed to be the design swelling pressure, the following mean values are obtained after swelling-out and homogenisation:

$e = 0.75$

$\rho_d = 1590$ kg/m^3 (dry density)

$\rho_m = 2020$ kg/m^3 (density at water saturation)

These mean values require either that the blocks be compacted to lower original dry density, which can be achieved by using a lower compaction pressure, or that the blocks are made smaller, which can be accomplished by reducing their diameter.

Evenness of swelling pressure

A preliminary conclusion from the ongoing investigation of drilling samples from the TBM tunnel at Äspö shows that a rich network of fine fractures is formed to a depth of about 5 mm from the surface and that occasional fractures several centimetres in length are formed parallel to and more or less perpendicular to the wall of the hole. The hydraulic conductivity of the rock up to a distance of 5 mm from the free surface can be estimated to be at least two orders of magnitude higher than in the undisturbed crystal matrix. This superficial zone can, therefore, at best be assumed to act as a distributor of water that is conducted from the host rock to the deposition holes via one of the few larger hydraulically active discontinuities that are assumed to intersect each deposition hole. This hypothesis is at least, in part, supported by the observation from Stripa BMT where the outer part of the bentonite buffer in six holes with a diameter of 0.76 m and a depth of 3 m and with different amounts of water had a very even and high water content. By contrast, the water content in the inner part varied greatly between the holes.

The wetting process can be described as follows. When the groundwater pressure starts to build up after emplacement of canister and buffer, water enters via the most conductive fractures that intersect the holes. The bentonite is saturated rapidly at the fracture openings and blocks them. Here the water pressure builds up and forces additional water to flow sideways around the holes in the superficial excavation-disturbed zone, where the flow resistance is lowest. The water penetrates most easily through the isolated boring-induced individual fractures where the buffer is wetted, swells and seals the fracture. This in turn forces the water to find its way through the many fine fissures in the boring-disturbed zone and up to the buffer contact. Buffer clay does not penetrate into fissures with an aperture smaller than about 150 µm, so they continue to act as conductors of water to the buffer. There is, however, uncertainty regarding the interaction between buffer and rock if the water flow rate to the excavation-disturbed zone is low.

Despite the fact that the swelling pressure is expected to build up evenly for these reasons, there are uncertainties regarding the interaction and there is reason to assume that there may be some inhomogeneity in the pressure build-up.

During the water saturation phase

Three cases should be investigated. They are simple to calculate but not entirely realistic, since the degree of restraint and pressure differences are exaggerated. If the canister cannot withstand these cases, more realistic studies should be conducted.

Case 1: Canister rigidly fixed at the end surfaces and about 0.5 m along the cylindrical surface nearest the end surfaces. An evenly distributed horizontal load of 10 MPa along one side of the whole remaining canister surface.

Case 2: Canister simply supported along approx. 0.5 m of the cylindrical surface nearest the ends. Same load as in case 1.

Case 3: Canister rigidly fixed at one end surface and about 1.0 m along the cylindrical surface nearest this end surface. Same load as in case 1.

These cases occur without water pressure.

After water saturation

If the canister is slightly tilted or inclined in the emplacement hole, or if the rock is uneven, a permanent pressure disequilibrium can exist in the bentonite even after water saturation. This can also occur due to swelling of the buffer at the top of the hole. The maximum size of the pressure disequilibrium is difficult to estimate. Some cases should be design-basis and some should be checked.

The following cases are design-basis:

- Full swelling pressure on one side of the canister's cylindrical surface and end surfaces. On the other side of the cylindrical surface, 20% elevated swelling pressure prevails along the central half and 20% reduced swelling pressure along the remaining quarters.
- Full swelling pressure around the lower half of the canister. 20% lower swelling pressure against the upper half. The resulting upward force, which results from the differences in pressure on the canister's end surfaces, is balanced by a shear force along the bottom half of the cylindrical surface.

These cases are evaluated with full water pressure added.

The following cases should be checked. If the canister cannot withstand these cases, more realistic studies should be conducted.

- Full swelling pressure on one side of the canister's cylindrical surface and the end surfaces. On the other side of the cylindrical surface, 50% elevated swelling pressure prevails along the central half and 50% reduced swelling pressure along the remaining quarters.
- Full swelling pressure around the lower half of the canister. 50% lower swelling pressure on the upper half. The resulting upward force, which results from the differences in pressure on the canister's end surfaces, is balanced by a shear force along the bottom half of the cylindrical surface.

These cases are evaluated with full water pressure but without a safety factor.

LOAD FROM DISPLACEMENTS

Pressure increments on buffer and canister can occur as a consequence of tectonics caused by regional stress changes and glaciation. Three factors determine the size of the pressure-exerting displacements: 1) the structure of the rock, especially the presence of planes of weakness along which movements can take place, 2) the stresses that can be absorbed in such planes, and 3) the quantity of energy that is released by the tectonic event. If the latter factor is expressed in the form of earthquake magnitudes, the following conclusion has been drawn. Earthquakes with a magnitude of 2–3 are associated with rapid displacements along large fracture zones of 50–100 mm while those with a magnitude of 8.3 lead to displacement up to 1.4 m (Pusch 1994). A magnitude of 5 can be estimated to cause instantaneous 200 mm displacements along discontinuities of large zones and generate 50 mm displacements along small fracture zones. Earthquakes of the latter size are judged to be able to cause an instantaneous displacement of no more than 1 mm along individual fracture planes that are judged to be able to intersect the deposition holes. The aforesaid displacements discussed above can be calculated on the basis of a generalised fractal-like, hierarchic rock structure that resembles that identified at several places in Sweden, including Finnsjön and Forsmark (Pusch 1995). Deviations from this structure type are not expected to entail large deviations in movement.

It is likely that repeated tectonic events will cause cumulative displacement along the different weaknesses. A magnitude of 5 can thus result in a displacement of 0.0005 to 0.001 m along planes that intersect deposition holes. It is reasonable to assume that the frequency of quakes of such a high magnitude as 5 is exceedingly low, perhaps one in 1,000 years. In 10,000 years the total displacement would therefore not be greater than 0.01 m, and in 100,000 years about 0.1 m. Since a glaciation and deglaciation are expected to occur after 10,000 years, the stress field then will change but the displacements caused by a glaciation cycle of the same extent as the greatest of the most recent glaciations will not be a decisive factor for canister design. Thus, the assessment is that shear movements in conjunction with the build-up and subsequent relief of ice pressure on glacial advance and retreat will mainly occur along steeply dipping weaknesses in the rock, causing insignificant mechanical stress on the canister.

A reasonable assumption in designing the canisters is, therefore, that the aggregate displacement along shallow-dipping fractures that intersect deposition holes can be 0.1 m during the next few tens of thousand years.

Lithostatic pressure

Theoretically, the rock deformations that occur under the state of stress created by the extraction of rock for construction of the final repository can be of importance due to creep. The diameter of the deposition holes could decrease by up to 1 cm in 1,000 years (Pusch 1994). In practice, creep can only be significant if it occurs along fractures with considerable extent in their own plane and is judged to cause minor deformations. The conclusion is therefore that there will not be any significant change in the size and shape of the deposition holes during the first 10,000 years after closure. Consequently, the impact of lithostatic pressure on the state of stress in the buffer and canister will be insignificant.

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